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Discord as a Quantum Resource for Bi-Partite Communication

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Abstract. Coherent interactions that generate negligible entanglement can still exhibit unique quantum behaviour. This observation has motivated a search beyond entanglement for a complete description of all quantum correlations. Quantum discord is a promising candidate. Here, we experimentally demonstrate that under certain measurement constraints, discord between bipartite systems can be consumed to encode information that can only be accessed by coherent quantum interactions. The inability to access this information by any other means allows us to use discord to directly quantify this 'quantum advantage'.

Keywords: discord, quantum information, quantum correlations
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INTRODUCTION

Often, the notion of advantage afforded by quantum information protocols was equated with the notion of entanglement. Recently, the requirement of entanglement to preform efficient quantum computation has been questioned both theoretically and experimentally [1, 2]. It has been proposed that, for certain mixed state quantum computing protocols, a non-classical quantity called quantum discord is all that is required for speed-up. Discord arises from the discrepancy between the quantum analogues of the two classically equivalent expressions for the mutual information: $I(\rho) = S(\rho_a) + S(\rho_b) - S(\rho)$ and $J_a(\rho) = S(\rho_b) - S(\rho_b|\rho_a)$. The discord, $\delta(\rho) = I(\rho) - J_a(\rho)$, captures all the non-classical correlations in ρ [3, 4], and is proving to be a popular candidate to provide a more complete the description of quantum correlations. .

Discord is a far more robust than entanglement. Quantum systems that have lost all entanglement due to environmental noise can still retain significant amount of discord. However, explicit protocols that directly exploit discord as a quantum resource have remained elusive and it remains unclear whether the operational advantage of quantum interactions is due to its capacity to harness discord, or if the presence of discord in such protocols is merely coincidental.

Here, we outline and experimentally verify a new protocol that directly relates the discord of a bipartite system to the processing advantage provided by coherent quantum interactions.

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THEORY

In oue protocol, Alice begins with some classically correlated bipartite quantum system ρ_{ab}. She then privately encodes a random variable X with probability $Pr(\mathbf{X} = x) = p_x$ onto one of her subsystems by application of a suitable unitary rotation U_x . The preparation and encoding scheme is publicly announced. Alice then gives the resulting state to Bob and challenges him to retrieve his best possible estimate of X. Upon receipt of Bob's estimate $\mathbf{X_o}$, Alice can quantify Bob's performance by the classical mutual information $\mathrm{I}(\mathbf{X_o} : \mathbf{X})$. Let I_c be Bob's best possible performance when he is restricted to a single local measurement on each subsystem a and b and classical post-processing. Let I_q be Bob's maximum performance when he can, in addition, implement arbitrary quantum operations between a and b, and thus effectively optimise his performance over all possible basis measurements of the joint system ρ_{ab}. The difference $\Delta I = I_q - I_c$ defines the extra quantum advantage that coherent quantum interactions can potentially deliver.

In [5] we prove that this advantage is directly bounded above by the amount of discord that was consumed when Alice encoded the information. In particular, $\Delta I \leq \delta - \tilde{\delta}$, where δ and $\tilde{\delta}$ respectively quantify the discord within the bipartite system before and after encoding. If the system contained zero discord, coherent interactions permit no advantage. This bound can always be saturated and discord can be consumed in its entirety. For an arbitrary bipartite state in arbitrary dimensions, Alice can always choose an encoding such that all discord is consumed. In this scenario, $\Delta I = \delta$. The advantage of having unrestricted quantum processing is given exactly by the amount of discorded available.

EXPERIMENT

We generate a non-entangled discordant state ρ_{ab} on two spatially separated subsystems by local operations and classical communication, thus ensuring that any observed advantage of coherent interactions is due solely to discord. This is experimentally realised by the encoding of correlated (anti-correlated) Gaussian white noise of variance V_s on the phase (amplitude) quadrature of the sidebands of two coherent states. Discord is consumed by encoding a classical variable X on one subsystem, corresponding to the encoding of additional white noise on the phase and amplitude quadrature of one subsystem. We then consider two scenarios: Bob attempts to estimate X in a basis that requires the coherent interaction of a and b, and Bob's best measurement of X given the restriction to a single local measurement on each subsystem and classical communication. To obtain a rigorous upper bound for I_C we characterise the encoded bi-partite system, and consider the Holevo bound for a perfect experimental realisation of $\tilde{\rho}_{ab}$. Although our estimate I_Q^{exp} does not correspond to the experimental realisation of the optimal coherent interaction and decoding protocol, it is sufficient to demonstrate an advantage $\Delta I^{exp} \geq 0$. This experimentally corresponds to the interfering subsystems a and b in phase on a 50:50 beam splitter, and homodyne measurement of the phase and amplitude quadratures of the resulting two modes. Provided $I_Q^{exp} - I_C = I_{exp} > 0$, we can then guarantee that our interactions are indeed coherent, and allow extraction of I_{exp} bits beyond the incoherent limit.

RESULTS

In Figure 1 we consider our measured quantum advantage ΔI as a function of the variance of the encode signal V_s. As we increase the strength of the encoded signal, progressively more of this initial resource is consumed (Figure 1.b), and thus bounds how much of this discord can be potentially harnessed (Figure 1.c). In an ideal version of the decoding protocol, the advantage would increase monotonically with the signal strength (Figure 1.d). With our imperfect experimental setup, there exists a saturation point around $V_s \simeq 20$, beyond which the extra theoretical gain from increased signal strength is offset by the extra experimental imperfections in encoding. This is attributed to the nonlinear response of the electro-optic modulators. When we include these imperfections within our theoretical model, observations and theory agree (Figure 1.d).

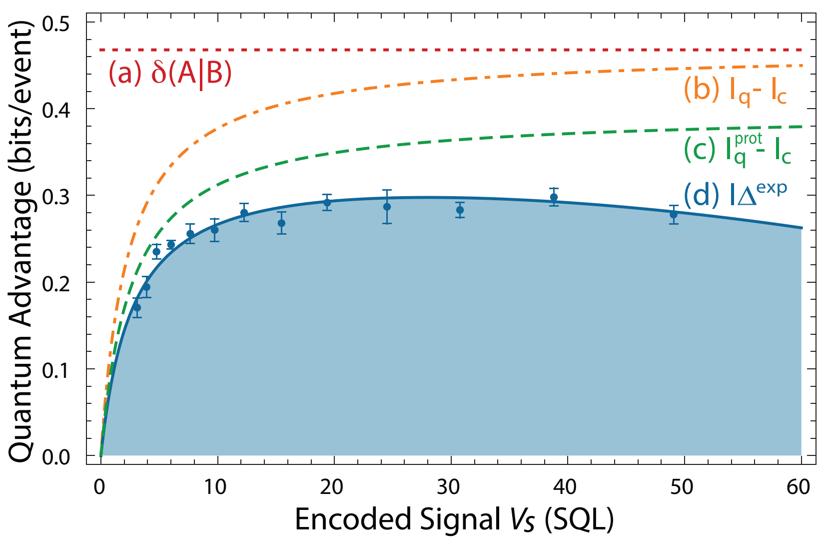

FIGURE 1. Plot of quantum advantage for varying signal strength with $V = 10.0 \pm 0.1$. (b) corresponds to the maximum possible quantum advantage, assuming Bob can perform an ideal decoding protocol. In the limit of large V_s, this tends to the discord of the original resource (a). The actual advantage that can be harnessed by our proposed protocol is represented by (c). In practice, experimental imperfections reduce the experimentally measured advantage to (d).

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